3D Modelling and Animation Study of the Industrial Heritage Wonders

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Abstract The paper describes the process of creating a virtual representation of some of the drawings made by the famous engineer and genius Agustin de Betancourt y Molina (Fig. 1). The latest technologies were used to recreate some of the engineering designs he painted with extreme detail to be part of a documentary directed by Desiree Hernandez Hormiga. No real physical simulation was intended, just an artistic interpretation of the environment, while maintaining a very approximate animation of such models.

Everything will be covered from gathering the right material to the study of movement and the correct approach at animating the wonders.

1 Introduction

When approaching such a task of bringing to life the ideas of another man, be he a genius or a madman, one must always feel humble and act carefully. The project that fell into my hands was a very exciting and intriguing task, to recreate three drawings made by Agustin de Betancourt y Molina. This notable man was one of the most influential and acclaimed engineers of his time. Working for the crown of Spain, gathering covert intelligence on the revolutionary steam engine, becoming a legend in Russia… The story of this man was truly fascinating. The more research I made, the more I realized that not only was Betancourt a great engineer, but a great artist too. His drawings had a beautiful finish, but also an extreme attention to detail. This attention to detail would prove later on very valuable.

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Fig. 1 A painting of Agustin de Betancourt y Molina (1758–1824)

2 Betancourt and His Works

For the purposes of this article, three industrial wonders have been chosen from thousands of ideas and paintings created by Betancourt.

The first one was the design of a Watt's steam engine with double-action (Fig. 2). The story behind this painting was truly fascinating. In 1789, Betancourt traveled to England, to meet the famous inventor James Watt. He was kindly received by the inventor, but he was shown everything except what Agustin was really there for, the steam engine. Disappointed, Betancourt went back to London. Still determined to see the engine, he contacted a friend and went to Albion Mills, at Blackfriars, where one of those engines had been recently placed. What is fascinating is that being able to only partially see the engine, at a certain distance, and only a glance, was enough for Betancourt to understand the mechanics behind the new steam engine of double-action. Once he went back to France, he started with the drawings. Not happy with what is probably one of the first examples of industrial espionage, Betancourt allied with the Périer brothers, and in less than a year, 1790, they constructed the first steam engine of double-action on the continent. This was truly a history-changing episode, as we do not know what would have happened if England had been the only country to control the steam engine. The reaction from England was not long in coming, and Watt wrote to Boulton, recommending that he be wary of foreigners. The knowledge of the steam engine grew

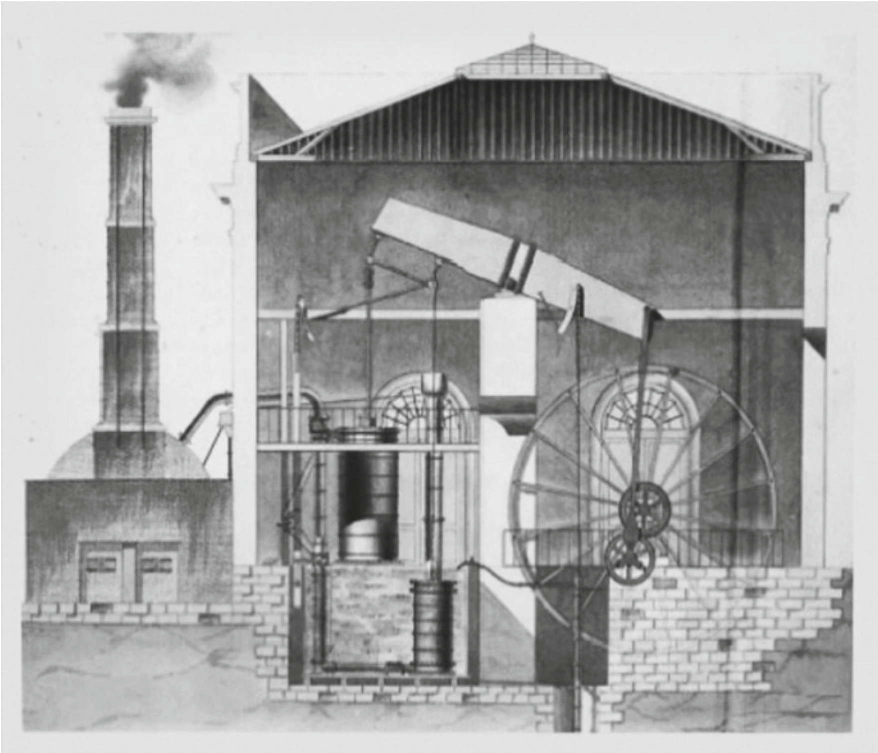

Fig. 2 A painting of the steam engine of double-effect (1789)

rapidly throughout Europe, affecting the complex phenomenon called the Industrial Revolution. The story can be found in Prony´s "Nouvelle Architecture hydraulyque" (I, page 572).

The second wonder that was selected was a water mill, designed to grind flints (Fig. 3). This was a very creative design, and it stands out from the rest because the mill could change the position of the waterwheel depending on the river flow, and the height of the water. The waterwheel was on top of two floating wooden devices, which could change its vertical position depending on how much water the river carried. The design was published in "An 18th century engineer's sketch book. William Reynolds book". Another sketch of this same mill can be found in Saint Petersburg, in the State University. There is no proof that the actual mill was ever constructed, still the design is made up from numerous paintings, in which Betancourt describes carefully how to make one of these marvels.

The third and last engineering wonder was the Kronstadt dredger (Fig. 4). The story behind this design is also full of anecdotes. In 1791, soon after taking part in study of the steam engine of double-action, Betancourt tried to design what would eventually be a steam-powered dredger. Taking the designs from the German

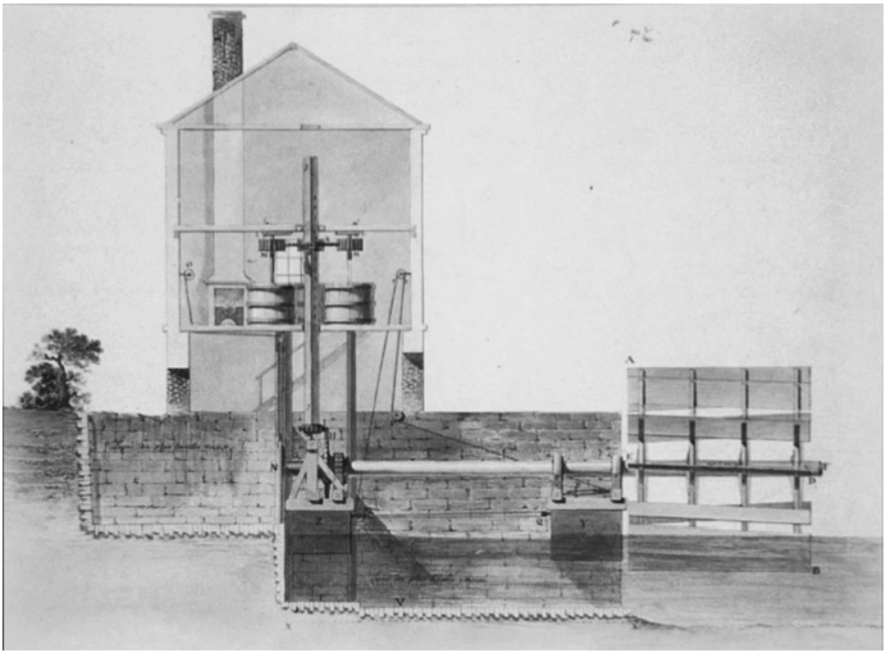

Fig. 3 A painting of the floating water mill

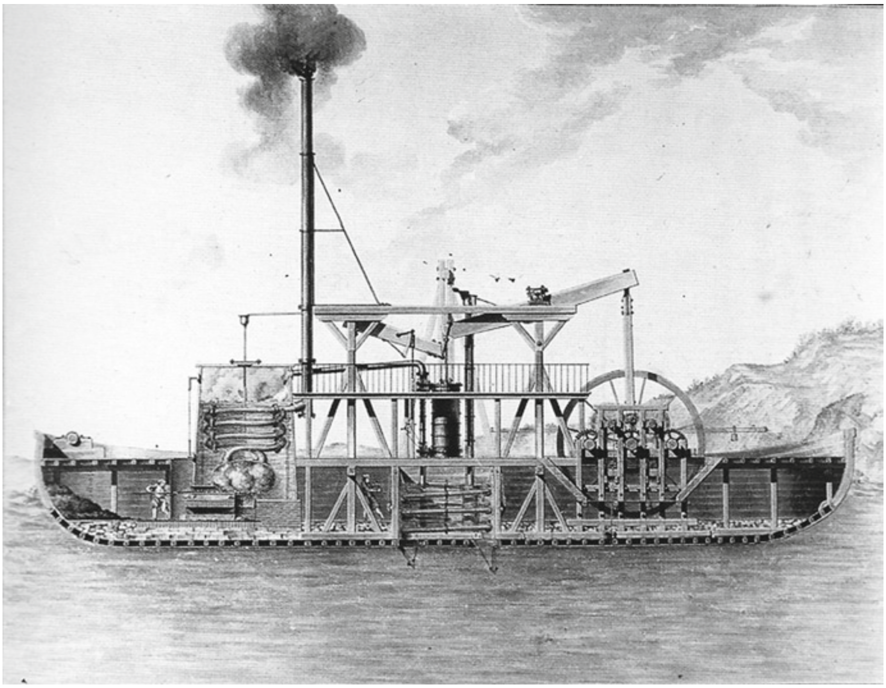

Fig. 4 A painting of the Kronstadt dredger (1810)

engineer Meyer, who invented the dredger powered by beasts, Betancourt penciled the steam engine dredger of double effect. The Spanish navy, pleading that the machine was too powerful, dismissed his pioneering design. This dredger was never constructed in Spain; Betancourt had to wait 18 years to see his vision come true. It was when he lived in Russia that he saw the opportunity of creating this steam dredger. Kronstadt was an island on the Finnish gulf of great strategic importance. It defended the city of Saint Petersburg from the seaside. In 1810, Agustin was given the task of making this steam dredger, using the best part of a year. It was finished in August 1811. In September of that same year Betancourt tried it and retouched some areas and in August 1812 the dredger arrived in Kronstadt. It worked full time until 1820, a year in which they made some repairs. Apart from this dredger, Betancourt designed another one of smaller proportions for cleaning the basin of the River Neva.

After considering which engineering marvels where going to be recreated in a virtual environment, the next step was to do some "geographical" research. If the task was to recreate these machines in the best possible manner, it was equally important to place these marvels in the right location. Photographs from different places were used as reference material to get an approximate idea of what was needed for the backgrounds, and what other elements the machines would be interacting with. In the example of the water mill and the dredger, it was clear that a correct river environment was required. How this was done will be discussed in the Post-Production section.

3 Modelling in 3D

The program chosen for the 3D modelling and animation of Betancourt's drawings was Autodesk Maya. Maya is an industry-standard software used in countless films and games. Having a large number of tools at our disposal, we concluded that Maya was the right choice for the task.

At the beginning polygonal modelling was used to outline the drawing's main features. A polygonal mesh is made from line segments that connect points in 3D space, called vertices (Fig. 5).

The vast majority of 3D models today are built as textured polygonal models, because they are flexible and because computers can render them so quickly. However, polygons are planar and can only approximate curved surfaces using many polygons. Most of the time these polygons will be triangular, being a complete mayhem to control, especially when modelling and texturing. The key here was to keep all faces of the model in quads (name given to a face with four vertices). The vast majority of the models were created with simple cubes, which then would be shaped using a technique called box modelling. This technique is used in 3D modelling to create complex shapes using simple cubes. There are two basic operations that make up this technique. Extrude is the main tool for this operation, it lets you take a face from the surface of a model, and elongate its position with newly created faces at its sides (Fig. 6).

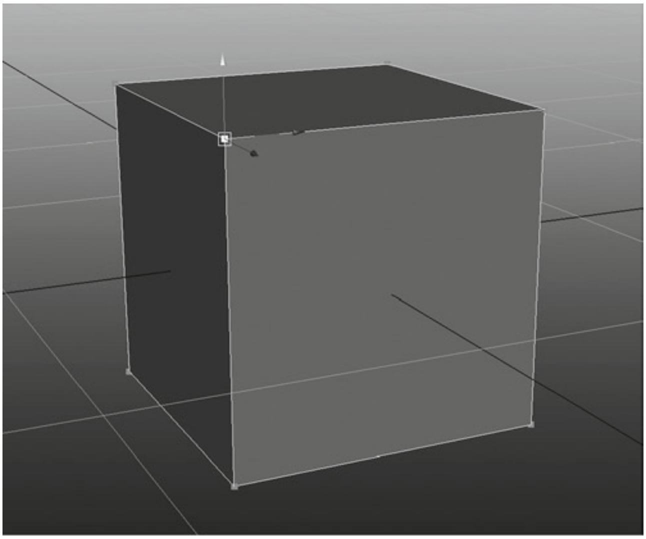

Fig. 5 A polygonal model showing the vertices, edges and faces

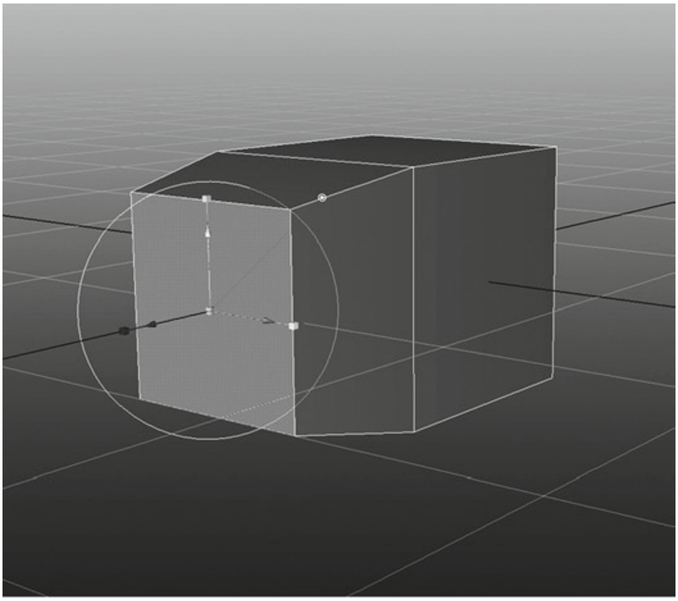

Fig. 6 The extrude operation with a slight scale difference

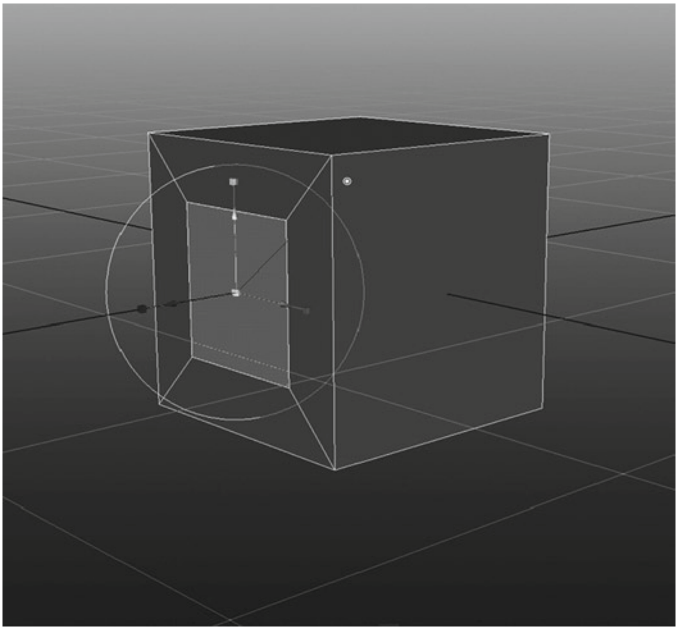

Fig. 7 The inner extrude operation

The next tool could be described as an “Inner Extrude” (Fig. 7).

This technique is quite similar to the extrude operation, except that the face chosen is now made smaller, creating new faces to the sides to fill in the area of the original face.

With these two basic operations you can model almost anything, you only need practice and expertise to master box modelling. The reason why many designers use it to create organic shapes is that, later on, one can apply a smoothing function to the mesh, creating curves where edges used to be.

Thanks to the extreme detail of Agustin de Betancourt’s paintings, the modelling was quite simple. The only consideration about modelling came when creating the different tubes and chimneys of the models. NURBS modelling was used to create all tube-shaped objects (Fig. 8). NURBS stands for Non-Uniform Rational Basis Spline; it is basically a mathematical model, commonly used in computer graphics for generating and representing curves and surfaces, that offers great flexibility and precision for handling both analytic and freeform shapes. Thanks to this technique, the accuracy of the modelling was doubled, due to the flexibility of the control vertex points of the mesh.

It was agreed early in the production stage that the models would represent only Agustin’s machines. No extra modelling was needed, epecially the characters that would appear if there was a need to show any human interaction with the machines. The other elements such as background or water would be created using post-production programs such as After Effects.

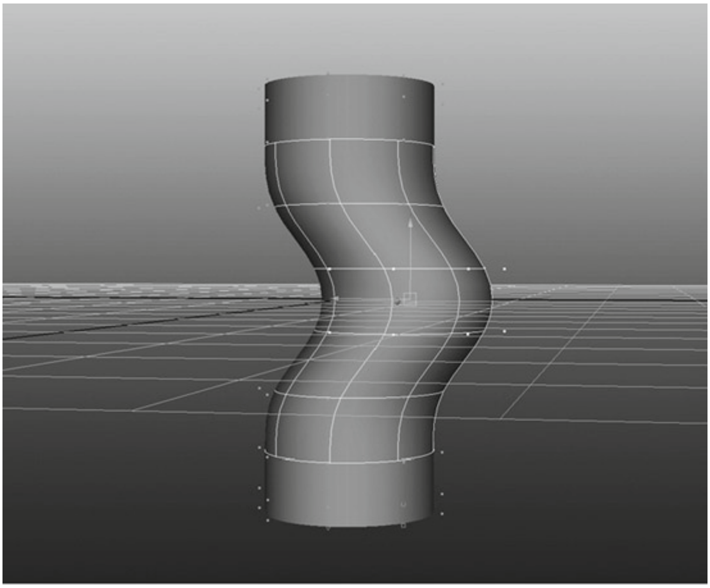

Fig. 8 NURBS being modified and returning a smooth surface

4 Applying Textures

It is a healthy habit to texture your models immediately after modelling them. The main reason is that if animation has been applied before the texturing process, "dancing textures" could appear, making the animation look strange and unprofessional. These so-called "dancing textures" are simply wrong interpretations of the UV points that are wrapped around the surface of an object in order to tell the 3D program where to show what part of the 2D texture.

Straight photographs were taken of all textures and processed first in Photoshop. A lot of research was required to find materials similar to those that would have been used during that period of time. Especially, woods and metals were used and a few concrete and dirt materials.

In any attempt to create professional looking textures, you need to have different parameters that will create what is called a material, or shader. These parameters will usually be the colour, bump map, displacement map, reflection, refraction, and a long list of others. In the case of recreating materials such as wood and metal, only the colour map, bump map, displacement map, reflection (on metal), and specularity (also metal) were used. Different files feed all these parameters. For example, the colour map is fed by a coloured photograph or composition. The rest of the maps are black and white images. The greyscale of the maps is translated to a range of values. Usually blacks are low values and whites are high values. The easiest way of illustrating this is probably using the reflection map as an example.

The areas of the map that are white will be reflective and all areas with black will be opaque, while all grey areas will be partially reflective, depending on the amount of black or white that the grey might have. A great tip for anyone who is looking to get a good bump map from a photograph is to use the red channel as the bump map. Colour channels in photographic programs are represented in a greyscale. So the famous RGB (Red, Green, and Blue), are actually greyscale maps that tell the program the amount of red, green or blue that must be applied to a certain area according to the same criteria as the other maps, using the greyscale as a scale of values.

A usual practice in the 3D profession is to “dirt-up” your models. This practice became quite renowned after the first 3D models looked too clean, or perfect. One of the goals of a good 3D artist is to try and mimic as best as possible the real world. Most of the time when doing research the 3D artist tends to look for the imperfections of the real world, since this does not occur in a computer environment. Textures are a crucial part of getting this realistic aspect of the scene.

Once the textures were chosen, the next stage was to set out the UV mapping. UV mapping could be explained as a 3D modelling process of making a 2D image representing a 3D model (Fig. 9). The map transforms the 3D object onto an image known as a texture map. In contrast to “X”, “Y” and “Z”, which are the coordinates for the original 3D object in the modelling space, “U” and “V” are the coordinates of the transformed object. This creates the effect of painting the image onto the surface of the 3D object. This task was quite simple, as most of the modelling was made out of extruded boxes: being all polygons it is easy to access the UV points throughout the UV editor.

Even so, the key to getting a successful UV map is to know how to project the map to the surface. There are different methods of wrapping the texture on to the object. These operations usually employ geometric shapes, such as square, cylinder, planar, or spherical projections (ideal for planets and beach balls!). There is also an

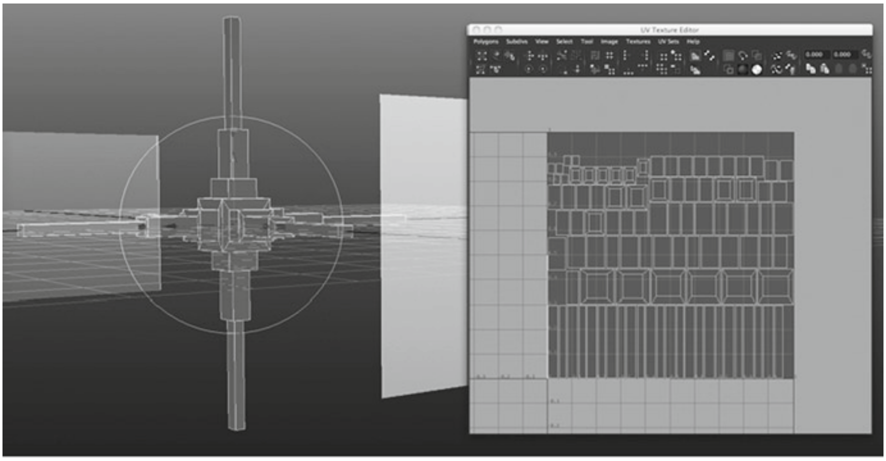

Fig. 9 UV mapping example

automatic way of making the UV texture: basically it takes every single face, and lays each one next to another. The problem with this procedure is that it creates very unpredictable UV maps, as adjoining faces from the chosen shape are usually not projected next to each other, so to paint or position different types of graphics on that map is not sufficiently coherent. Ideally, you want to use one of the geometric projections mentioned above, and then manually reconstruct the shape of the object so it is recognizable when you attempt to lay down the textures.

Some of the shadows were baked to lower rendering times, as there was a tight schedule. Baking shadows is a process by which the renderer calculates where the shadows will be cast to a surface, and then apply this information to literally become part of that surface. This translates to literally painting the shadows on the actual texture. This is a great choice for obvious reasons, but only if you are completely sure that the light's position, direction and intensity are correct. The main reason to gain speed by baking shadows is that the renderer overrides any calculation having to do with the trigonometry of the angles of light being cast and hence creating shadows. This operation is usually the part that takes longer to render, especially if you use Final Gathering.

5 Animation

This was by far the most exciting and inspiring part of the whole process. Long sleepless nights were spent to try to figure out how all these machines could be animated in an efficient way, while keeping some sort of realism. At the beginning the task seemed to be quite simple, as no accurate simulation was needed. But the animations had to look "believable", which actually made it much harder than planned.

There is something about motion that the human eye can pick up quite easily. Its astonishing to see how one tries to animate a scene following the right "scientific" way and after seeing a quick render, the eye tells you its not right. I found the hardest task was to fool the mind of the viewer into seeing the animation as something natural. Actually, the whole purpose was to make the viewer see the animation but not necessarily take too much notice of it, letting the mind discover the shapes and textures of the models.

The first approach was made through traditional key frame animation. A key frame in animation and filmmaking is a drawing that defines the starting and ending points of any smooth transition. They are called "frames" because their position in time is measured in frames on a strip of film. A sequence of keyframes defines which movement the spectator will see, whereas the position of the keyframes on the film, video or animation defines the timing of the movement. Because only two or three keyframes over the span of a second do not create the illusion of movement, the remaining frames are filled with in-betweens (Fig. 10).

Soon this technique proved to be very tedious and the animation seemed too "mechanical". Every element had to be animated separately, which made the process far too slow.

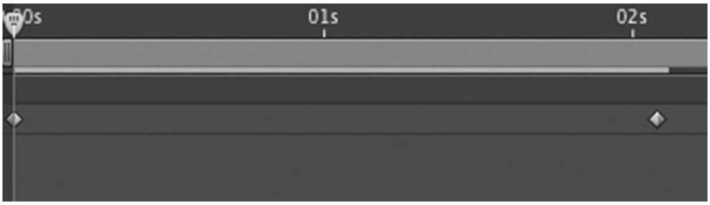

Fig. 10 Visual representation of keyframes

Fig. 11 Set driven key window

The next technique that was tried was to use set-driven keys. In Maya, set-driven keys are keys that link the attributes at their new values (Fig. 11). You can link the attributes with as many keys as necessary. The default interpolation between the keys is linear. To fine-tune the relationship between the driver attribute and driven attribute, use the Graph Editor. The Graph Editor is like the Holy Grail for any animator. In this procedure you see a visual representation of movement described by curves. The steeper the curve is, the faster the values will change, while the more horizontal the line is, the slower those values will change. This technique is extremely interesting, and it involves certain mathematical equations

to link parameters from one object to another. In theory the setting up of the animated scene takes quite a long time, but once everything is linked properly, it should be quite easy to see the results.

Still this second technique turned out to be very unpredictable. The animations lacked naturalness and some of the parameters did not match up, as one would have wanted them to do. The main problem resided in the rotational axis of the wheels (all three designs had some sort of wheels). Linking values that feed rotations with values that come from vertical movement proved to be quite hard to match.

Finally, and after a lot of thought about the animation technique, I decided to use the same technique used for characters: skeletal animation. Skeletal animation is a technique in computer animation, particularly in the animation of vertebrates, in which a character is represented in two parts: a surface representation used to draw the character (called the skin) and a hierarchical set of bones used for animation only (called the skeleton) (Fig. 12).

Bones will be created to form the skeleton, and thus the skeleton would deform the skin. Now it is crucial that the rotational axis of the skeleton is set properly at the start of the creation of the animated system. That means that all bones should have the x, y, and z-axis facing the same way, as if not, the animation would end up being chaotic and unpredictable. In this case the skin would be the parts of the engine. Now the reason why I did not try this technique before was because to do so, the model needs to have the right perfect proportions and the location of joints need to be extremely precise.

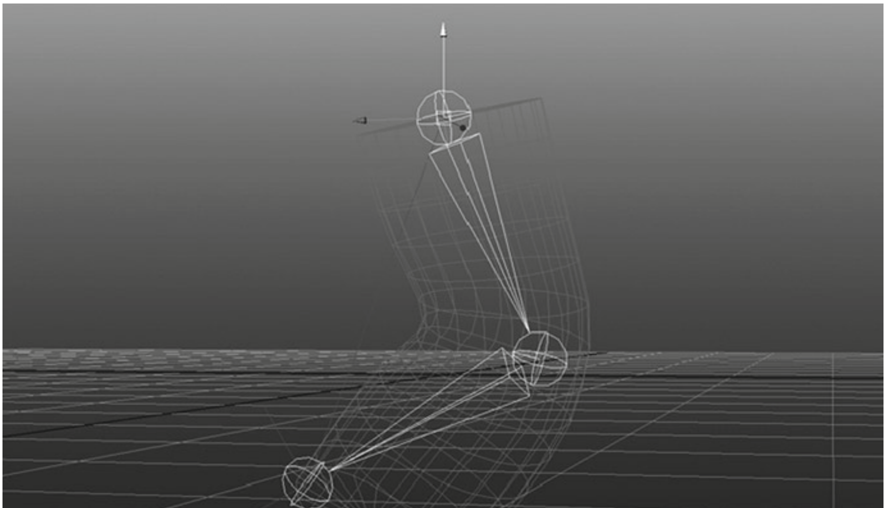

Fig. 12 A set of bones with inverse kinematics and skinning

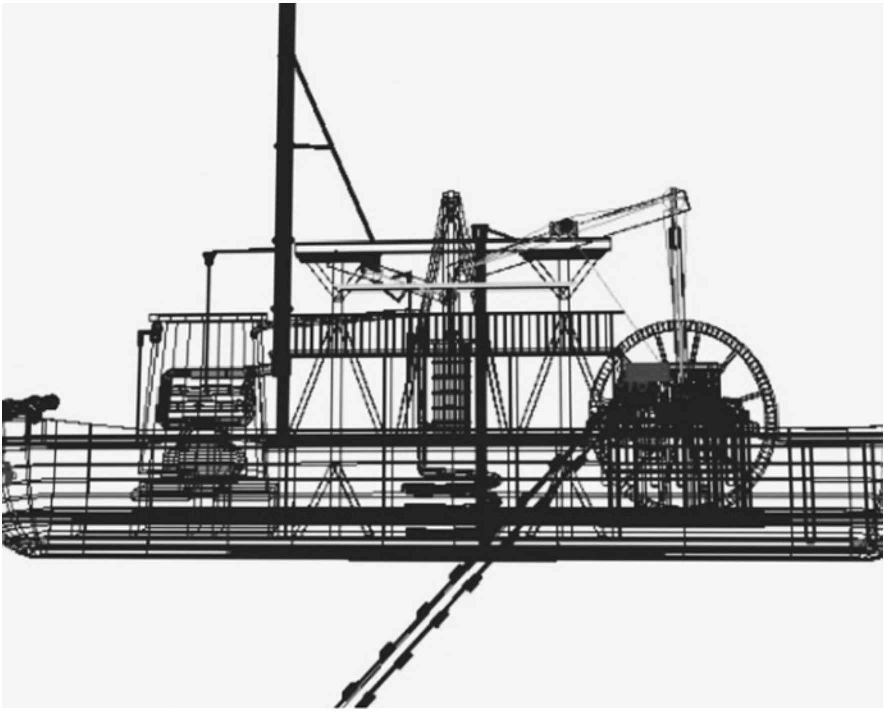

Fig. 13 A schematic view of the complex bone system or “rig”

Never before had I tried to animate an inanimate object with this technique. Following to the millimetre the drawings of Agustin to create the model, and having laid out an extremely complex bone and joint system with multiple hierarchies and constraints, I witnessed a miracle (Fig. 13).

In the end, only one parameter was animated with several key frames, and the whole system behaved accordingly, giving it an amazing feel of realism and naturalness to the motion. After a lot of research on how the steam engines would behave, I found myself with an animation, that was extremely close to being hyper-realistic. The only reason for such success was the incredible drawings of Agustin de Betancourt y Molina. His drawings were so perfect that, when it came to recreate them, they worked exactly as intended. This kind of experience humbled my perception of artistry. This man, centuries ago, was able to draw something that was computer-calculation accurate!

Once the technique was polished and the skeleton system was perfected, the animations took much less time than had been expected. The days lost in trying out different techniques were regained once again by the genius of Agustin. Everyday that I worked on his projects I felt closer to him.

Once the animations were finished, it only remained to light the scene and take it to post-production.

6 Lighting and Rendering

After all the process of animating the models in an accurate way, the final step was to light the scenes and render the files.

Lighting was approached in the most accurate way. Mental Ray was used to light the scene with an accurate Physical Sun and Physical Sky and applying Final Gathering. Mental Ray is a production-quality rendering application developed by Mental Images (Berlin, Germany). Nvidia bought Mental Images in December 2007. As the name implies, it supports ray tracing to generate images. In computer graphics, ray tracing is a technique for generating an image by tracing the path of light through pixels in an image plane and simulating the effects of its encounters with virtual objects. The technique is capable of producing a very high degree of visual realism, usually higher than that of typical scan line rendering methods, but at a greater computational cost. This makes ray tracing best suited for applications where the image can be rendered slowly ahead of time, such as in still images and film and television special effects, and more poorly suited for real-time applications like computer games where speed is critical. Ray tracing is capable of simulating a wide variety of optical effects, such as reflection and refraction, scattering, and chromatic aberration (Fig. 14).

A classic problem in computer graphics is lighting a scene solely through indirect light, like from a sky, or other “environment” light from an acquired HDRI or similar. High dynamic range imaging (HDRI or just HDR) is a set of techniques that allows a greater dynamic range of luminance between the lightest and darkest areas of an image than standard digital imaging techniques or photographic methods. This wider dynamic range allows HDR images to more accurately represent the wide range of intensity levels found in real scenes, ranging from direct sunlight to faint starlight. This is accomplished in Mental Ray using Final Gathering (henceforth

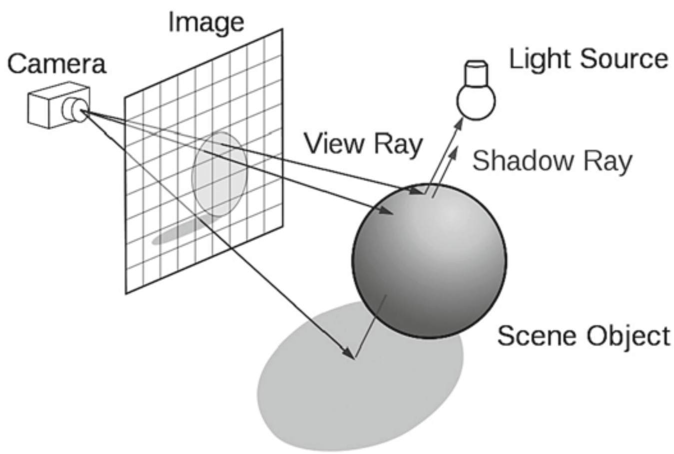

Fig. 14 Explanation of how Ray Trace works

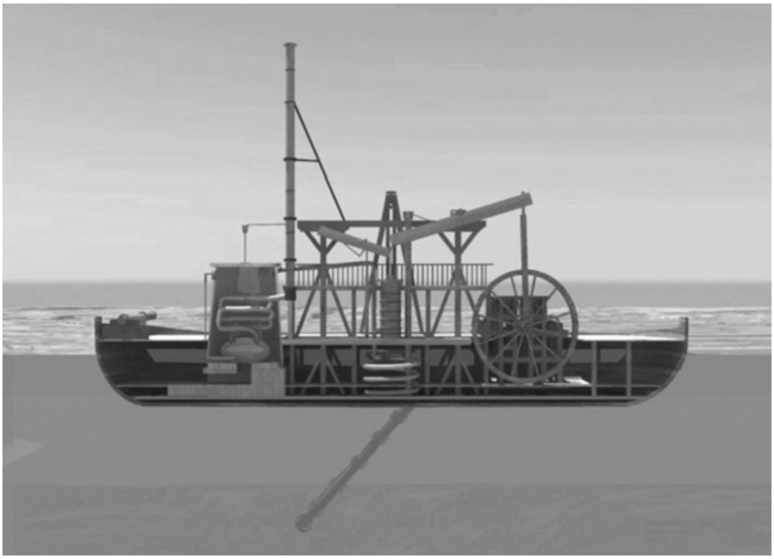

Fig. 15 Frame rendered with Final Gathering

abbreviated as FG), and is done by tracing a large number of “FG rays” to see which hit the environment (or other lit surfaces). Since this is a large number of rays, the results are cached (for performance) at FG points and the result is interpolated, “smoothing” the result. This all works very well when there is a lot of fairly uniform light that is “seen” by the FG rays. In general, FG gives the best result when the light levels in a scene are fairly uniform; it works well to illuminate an outdoors scene by the sky (most FG rays “see” the sky), and it works well to bounce secondary light in a room in which most surfaces are lit by direct lights (most FG rays “see” some already-lit surface) (Fig. 15). Notice the areas that are exposed to the sun directly and the areas inside the boat.

These tools let you light the scene with one single light that would act as the sun, plus a sky to create second lighting algorithms. This technique is very interesting, since it actually calculates the amount of light that bounces off the surfaces and thus lightens other parts of the scene or model. In a nutshell, it recreates real light behaviour.

This technique is very processor intensive, and also increases the rendering times, but since all the background would be added in post-production it was the best choice to render these scenes in the most photorealistic way.

After doing some test renders, some cameras were added to the scenes and animated accordingly so as to have enough shots for the editing in the documentary. The camera had smooth movements, to recreate a cinematic feeling to the shots. The advantage of 3D programs is that you can literally place the camera wherever you want on the scene, with no physical constraints. This is why some of the shots had extreme close-ups, in places that would have been unthinkable to do with a real camera. Once the test renders were done and the motion of the camera and objects

was approved, every single camera was rendered separately. Final Gathering was quite slow, and the average time for a frame to render was around 4 min. Taking to account that every second has 25 frames (PAL system was being used), you probably have a pretty good idea of the very long time it took.

The rendering output was set to TIF sequences to obtain a clean alpha channel that later on would be vital for the post-production process. There is a need right about now for a discussion of which formats to use when exporting your work in 3D. PNGs are a great choice for this kind of sequences especially if there is not much available space on your hard-drive. A PNG is basically a TIF but much more compressed. The key advantage of a PNG sequence is that it occupies less space on your hard-drive and that it also has transparency information, crucial for the next stage, post-production.

The rendering should be done in different passes, which implies that every visual effect, such as diffusion, the lights and their shadows, the reflection of refraction of the scene, etc. should be stored separately. The idea is to gain power later on in the post-production process.

My most crucial advice would be to keep control of all the files in separated folders, naming everything very carefully, as later on the task is to take all those rendered sequences and amalgamate them.

7 Post-production

Once the rendering was finished, all image sequences were imported into After Effects (Fig. 16).

Now all that remained to be done was to create the scene on which these drawings would appear. Research was done to determine what kind of geographical and

Fig. 16 After effects workspace

architectural elements could be used to give some sort of credibility for the animation. Photoshop was used to isolate the elements from photographs for later use in the background of the image. In the end, the backgrounds for each animation were a collage of multiple photographs that where positioned, scaled, and colour corrected in order to obtain a decent landscape. Also the rendering passes were imported into the program and placed in layers. The key to successful composition is to use the right blending modes to mix the layers.

Blend modes in digital image editing are used to determine how two layers are blended into each other. The default blend mode in most applications is simply to hide the lower layer with whatever is present in the top layer. However, as each pixel has a numerical representation, a large number of ways to blend two layers is possible. The currently most common numerical representation of colours is the one used in RGB (red, green, blue) images, where three numbers (x, y, z) can take values between 0 and 255, each of them indicating how much red, green and blue the pixel contains. This means for example that (255, 0, 0) is intense red and (0, 0, 255) is pure blue. There are other colour models, which have other number representations. For the purpose of blend modes, the principles are very similar for different colour models, even though not all blend modes can be applied with all colour models. These objects and render passes are placed in layers inside the composition program (Fig. 17).

After all preliminary positioning and blending was finished, the integration of the different elements was made through primary and secondary colour correction. Primary colour correction affects the whole image utilizing control over intensities of red, green, blue, gamma (midtones), shadows (blacks) and highlights (whites). Secondary correction brings about alterations in luminance, saturation and hue in six colours (red, green, blue, cyan, magenta, yellow). The main objective of secondary controls is to adjust values within a narrow range while having a minimum effect on the remainder of the colour spectrum. Using digital grading, objects and colour ranges within the scene can be isolated with precision and adjusted. Colour tints can be manipulated and visual treatments pushed to extremes not physically

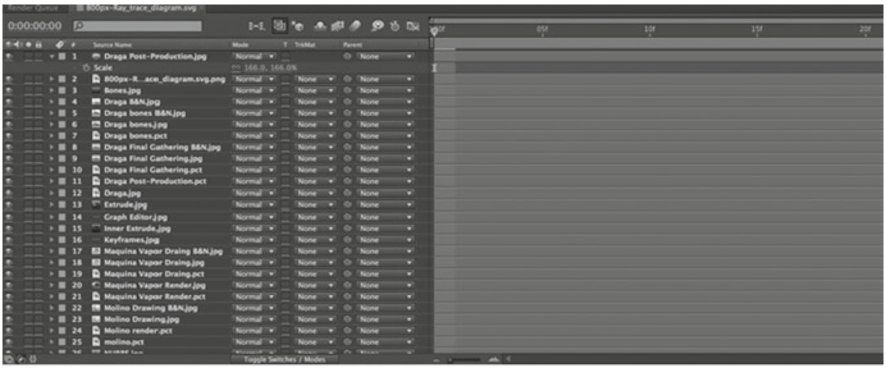

Fig. 17 Stacked layers with all the rendered passes

possible with laboratory processing. Special digital filters and effects can also be applied to the images. It was vital to match the shadows and highlights of the background with the foreground. Now this is probably one of the most difficult aspects of any compositing workflow. Making objects match. After using levels and curves to match the three channels (RGB), some more elements were added to create an atmosphere.

Also matching the film grain was a crucial part in making the shot work. Film grain or granularity is the random optical texture of processed photographic film due to the presence of small grains of a metallic silver developed from silver halide that have received enough photons. There are multiple effects that let you match the grain of different footage, but there is one in particular that works very well. That is "Match Grain" in After Effects. The reason it is so powerful is because you can actually change the amount of grain in every individual colour channel (RGB), obtaining the highest quality results.

After everything was in place particle systems were used to create smoke, fire and water splashes (Fig. 18).

The term particle system refers to a computer graphics technique to simulate certain fuzzy phenomena, which are otherwise very hard to reproduce with conventional rendering techniques. Examples of such phenomena that are commonly replicated using particle systems include fire, explosions, smoke, moving water, sparks, falling leaves, clouds, fog, snow, dust, meteor tails, hair, fur, grass, or abstract visual effects like glowing trails, magic spells, etc.

Once all the elements were added together and blended with each other using colour correction techniques, there was nothing left to do except to render the final clips and edit them into the documentary. The rendering time of these clips will take much less time, since the complex 3D calculations have been translated to pictures. In the end one ends up with something like this (Fig. 19).

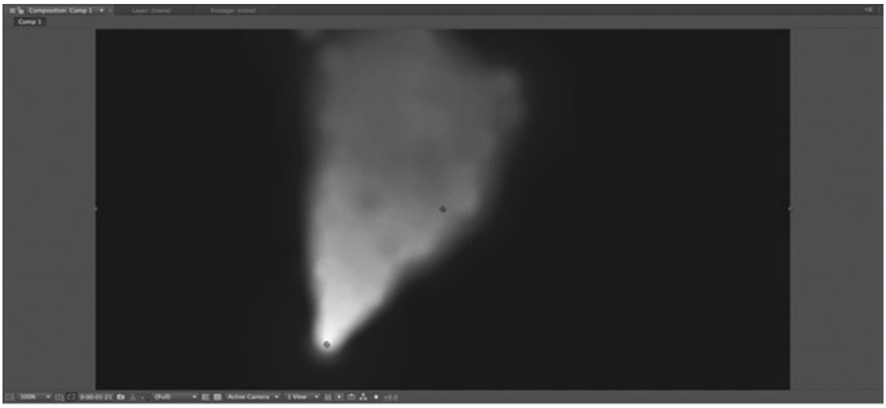

Fig. 18 Particle system as a smoke effect

Fig. 19 Final frame of all the elements in place

8 Conclusion

Working on this project made me realize the educational potential of this kind of animation. Once the tedious modeling and texture have been finished, being able to animate cameras from any angle, gives you the opportunity to watch the machine from points of view that in a normal world would be impossible. You can place cameras inside the machine to illustrate in a more visual way a complex interaction of pieces that otherwise would have needed to be explained with large, confusing diagrams. Once the model has been finished, you can modify as many times as you want the animations, giving you a limitless amount of possibilities in order to create educational content.

Times are changing, and education should change with the times. With these kinds of tools you can enhance the learning experience of students, helping in the understanding of different types of engineering concepts.

You also have the historical factor, as you can recreate very precisely engineering wonders lost in time, giving everyone the opportunity to have a look at the past, and understand better how those engineering wonders worked.

The next step would be to create a website where all these animations would be hosted, so that anyone could access thousands of years of knowledge. It would then be easy to create dynamic historical timelines of different machines, showing how the technology has evolved in the last thousands of years. For example, we could see the evolution of power through the usage of beasts, to the steam engine, to modern engines.

Making this proposed project into reality would lead to an incredible amount of information that would be accessible to anyone, anywhere in the world. It would be a great way to reach to potential engineers, to show them how engineering evolves, and to suggest where it could evolve to.

Fig. 20 Steam engine of double-action

Fig. 21 Water mill with floating waterwheel

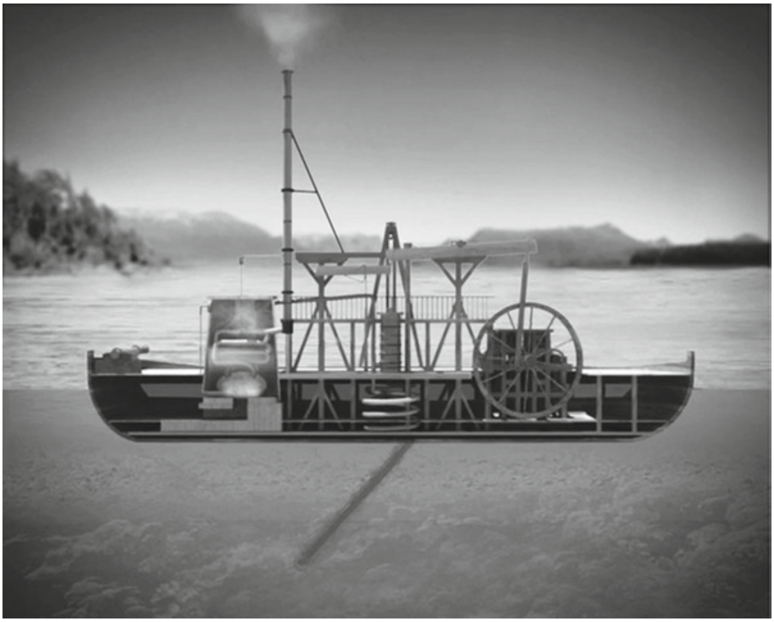

Fig. 22 The Kronstadt dredger

This not only implies a fantastic resource of information for future students, but also a source of inspiration. At the end of the day, the word engineering comes from the Latin word "ingenium", which can also be translated as "wit" or "to create", and is very similar to ingenious.

This project proved to be an incredible experience that steered my professional career in a direction I did not anticipate, and allowed me to discover a whole new avenue for creating animations based on engineering wonders.

These are the final results of the process described in this article (Figs. 20–22).

Bibliography

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